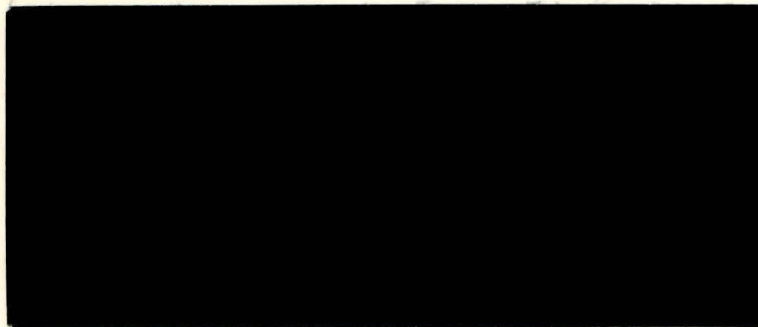


THESIS/REPORTS

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U. S. DEPARTMENT OF AGRICULTURE

PRODUCTIVITY AND RATES OF SUBSTITUTION
OF LINE BUILDING FORCES IN FIRE SUPPRESSION--
A SUMMARY OF EXISTING DATA

by

Theodore G. Storey

NOTE: Although we do not intend to publish this Progress Report, it has been carefully reviewed for technical accuracy. We are making a limited distribution to persons who may find it useful.

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SUMMARY

Existing data on the productivity and tradeoffs of nine types of fireline building forces in the United States are summarized, compared, and discussed. Data vary in quantity and quality depending on the force and section of the country. The Forest Service is by far the largest source of data mostly contained in "fireline notebooks," one per Region, designed for ease of use in the field. These are presented in the form of tables, graphs, slide rules, and alinement charts for the user's convenience. However, only handcrew and bulldozer data exist in any quantity and probably are obsolete since they are more than 25 years old. In only a few cases are the source data or reports available for checking. Tabular productivity for a given type of force were found to vary widely among Regions and apparently cannot be explained on the basis of different soil, fuel type, or other conditions. In some instances assumptions and units of production were not comparable. One Region found that existing handcrew rates were too high, probably because the original study was conducted under non-fire conditions. The methods, analytical techniques, and system for expressing results they used to restudy handcrew productivity is recommended to other Regions. Probably most bulldozer rates are obsolete because advances in equipment design have made contemporary machines more productive than their predecessors for which existing rates were developed. One State and Region are cooperating to test the new models. Explicit data on tradeoffs among forces for building fireline are almost entirely lacking. In practice, experienced judgement is the best way to estimate tradeoffs at the present time. The few existing dispatch-

ing and probability guides for predicting length of fire perimeter requiring action and for estimating forces required suffer from shortcomings of the basic productivity data and inadequate basic knowledge of fire behavior. Many factors affecting fire behavior and force productivity are not integral to the guides but are simply listed for the user's consideration and as guides to personal judgement. Existing productivity data for all types of forces generally are too scanty and inconsistent to implement mathematical models of initial attack and suppression of forest fires currently in development. In any case, they should be thoroughly checked before being widely used as input to the models.

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PRODUCTIVITY AND RATES OF SUBSTITUTION OF LINE BUILDING FORCES
IN FIRE SUPPRESSION - A SUMMARY OF EXISTING DATA

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INTRODUCTION

Several studies are developing mathematical models of initial attack and suppression of forest fires (Parks and Jewell 1962, McMasters 1963, Swersey 1963, Parks 1964, Jewell 1965, and McMasters 1966).^{1/}

^{1/} Bratten, F. W. A mathematical model for computer allocations of firefighting resources on large fires. (Manuscript in preparation, Pacific Southwest Forest & Range Exp. Sta., Riverside, Calif., 1969.)

Very simply the suppression job, usually the building of fireline, must progress at a more rapid rate than the fire perimeter increases in order to control the fire. Obviously, successful implementation of the models developed in the current and future work will require good quantitative input data on the productivity and comparative rates of substitution or "trade-offs" among the various line building forces. Included are hand crews, air attack, bulldozers, pumpers, plows, and combinations of these forces. A cursory examination of existing data suggests they are not adequate for the modeling studies, nor for research purposes in general. And at least one Region of the U. S. Forest Service has found through experience that its existing handcrew rates and bulldozer rates are

inaccurate or obsolete or both. It is working with research to develop better data.

This Progress Report presents, summarizes, and compares existing productivity data on a common basis nationwide for use in the modeling studies and by others studying fire control systems and tactics.

TYPES OF FORCES

There are nine different types of fireline-building forces in the United States: handcrews with hand tools, handcrews with power tools (circular saws, flail trenchers, etc.), smokejumpers, bulldozers, tractor-plows, air tankers, helitankers, pumpers, and helitack or helijump crews.

Certain forces are used in some sections of the country and not in others. For example, the tractor plow is used in the South but not very extensively in the West. The opposite holds true for the bulldozer.

Line width varies greatly by type of force and to some extent within force. The handline is commonly cleared to a width of five feet, including two and one-half feet scraped to mineral soil. On the other hand, the minimum width bulldozer line is one blade width--about nine feet wide, all scraped to mineral soil. The average plow line is about four feet wide. There appears to be some confusion among the experts as to whether or not and how much firelines, particularly handlines, should be widened or narrowed to allow for variable fire intensity and variable wind speed.

PRODUCTIVITY DATA

Most of the productivity data currently available were developed by the U. S. Forest Service. These data are contained in appropriate sections of the Forest Service Manual and of the Forest Service Handbook

for each Region. With one exception, each of the nine (formerly ten) Regions has summarized and published its productivity data and other fire suppression information in the form of a pocket-sized "fireline notebook" for ease of use in the field (U. S. Forest Service 1957, 1961, 1962, 1963, 1964, 1965a, 1965b, 1966b, 1966c). Productivity data from other sources are scattered among various published and unpublished articles and reports. Unfortunately, most of the basic data behind the tabular data are no longer available and it is difficult to check on the precision, accuracy, and assumptions of the original studies. Nearly all existing data are more than 25 years old.

Forest Service Sources

The various types of productivity data and associated data contained in the Forest Service "fireline notebooks" or manual supplements are summarized in Table 1. The data themselves will be summarized in the next section.

All Regions have data on the rate of handline production and all but one, R-8, include bulldozer production rates. None of the sources contain line production data for any type of aircraft.

Production rates for all forces are expressed as chains of line constructed per hour. This ties productivity to rate of perimeter increase of fire which also is expressed as chains per hour.

Some contiguous Regions use the same productivity data or these data slightly modified for certain types of force. For example, the three Forest Service Regions on the west coast of the conterminous United States (R-1, R-5, and R-6), use identical bulldozer line pro-

Table 1.--Summary of types of productivity data and associated data in Forest Service Manuals, Handbooks, and notebooks by force and Region.

ITEM	U. S. FOREST SERVICE REGIONS									
	1	2	3	4	5	6	7 ^{1/}	8	9	10
Notebook Form	Yes	Yes	Yes	Yes	Yes	Yes	-	-	Yes	Yes
Fuel Types (No.)	-	-	11	17+	17	13	15	20	38	6
Resistance to Control Types (No.)	4	4	4	4	-	2 ^{2/}	4	4	4	2 ^{2/}
Rate of Spread Types (No.)	5	-	4	4	-	-	4	4	4	-
Perimeter Rate of Spread	Yes	-	Yes	Yes	Yes	-	Yes	Yes	Yes	-
Production in Chains/Hr.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Handline Held Line Rate	-	-	Yes	Yes	Yes	-	Yes	Yes	Yes	-
Handline Construction Rate	Yes	Yes	-	-	Yes	Yes	-	-	-	Yes
Handline Holding Required	-	-	-	-	Yes	Yes	-	-	-	Yes
Production-Crew Size	Yes	-	-	-	-	-	-	-	Yes	-
Production-Crew Type	Yes	Yes	-	-	-	-	-	-	-	-
Fixed-Wing Aircraft Information	Yes	-	Yes	Yes	-	-	-	-	-	-
Fixed-Wing Air Tanker Information	Yes	-	Yes	Yes	Yes	-	-	-	-	-
Fixed-Wing Air Tanker Production Rate	-	-	-	-	-	-	-	-	-	-
Helicopter Information	Yes	-	-	-	-	-	-	-	-	-
Helitanker Information	-	-	Yes	Yes	Yes	-	-	-	-	-
Helitanker Production Rate	-	-	-	-	-	-	-	-	-	-

ITEM	U. S. FOREST SERVICE REGIONS									
	1	2	3	4	5	6	7 ^{1/}	8	9	10
Bulldozer Information	Yes	-	-	-	Yes	-	-	-	-	-
Bulldozer Production Rate	Yes	Yes	Yes	Yes	Yes	Yes	-	-	Yes	Yes
Flow Production Rate	-	-	-	-	-	-	-	Yes	Yes	-
Pumper Production Rate	-	-	-	-	-	-	-	-	Yes	-
Other Equipment Production Rate	-	-	-	-	-	-	-	-	-	-
Diagram of Organization	Yes	Yes	Yes	Yes	Yes	Yes	-	-	Yes	Yes
Dispatching Guide	-	-	-	-	-	-	Yes	Yes ^{3/}	-	-
Probability Guide	Yes ^{3/}	Yes	Yes	Yes ^{3/}	Yes ^{3/}	Yes ^{3/}	-	Yes ^{3/}	Yes ^{3/}	Yes

1/ Region 7 has been abolished and its former territory assigned to Regions 8 and 9. Productivity data in Manual Supplement form still bear the R-7 designation.

2/ For bulldozers only. For handcrews in other Regions.

3/ Fairly detailed guides for dispatching and/or calculations of probabilities. Guides for other Regions are brief.

duction rates although fuel types in the three Regions differ considerably in appearance.

All Regions but Region One and Region Two specifically list fire fuel types and all Regions excepting Region Five rate their fuel types for resistance to control. Six Regions base resistance ratings on handcrew productivity and use four rating classes. The remainder use two rating classes and base the ratings on bulldozer fireline productivity.

Only Region Nine has production rate data for pumpers and for tractor plows. Data are very brief and are expressed as trade-offs among these forces and bulldozers and handcrews.

Each Forest Service regional notebook or handbook contains one (all Regions except R-9) or two (R-9) guides for estimating the number of men and machines required to control a fire in a given situation. One type of guide is for dispatching on initial (first) attack (R-7 and R-9), the second for determining force requirements after initial attack has failed (all other Regions). Use of the latter type of guide usually is referred to as "calculating probabilities." Length of perimeter requiring action is estimated from current fire size, past behavior, and predicted rate of spread. Forces required to handle the length of perimeter indicated are estimated from productivity data such as those described earlier. Estimates are updated as better data from the scene of the fire become available. Fire size and rate of spread are implicit in the dispatching guide for Region 7 but are not actually computed.

Fuel type, fuel moisture, wind speed, and slope are among the factors considered in estimating rate of spread. As many as 13 other factors also

believed to influence fire spread are listed for the user's consideration and, in some guides, their expected effect is described qualitatively. The guides further warn that allowances must be made for possible breakdowns of equipment, delays, and unusual conditions. Guides vary considerably in detail with Regions 1, 4, 5, 6, and 9 guides most complete. Guides are designed for ease of use in the field. Computation aids include tables, graphs, alinement charts, and circular slide rules. Region 5 furnishes its probability guides in all four forms for the user's convenience.

All Sources

Productivity data from all sources by type of suppression force are summarized in this section. Sources in addition to the Forest Service notebooks include individuals in Forest Service administration (Hanson and Abell 1941, Stilling 1951, Ames 1953), Forest Service research^{2/ 3/}

^{2/} Lindquist, J. L. Probability estimates of handline construction rates. 1969. (Manuscript in preparation, Pacific Southwest Forest & Range Exp. Sta., Riverside, Calif.)

^{3/} Lindquist, J. L. Estimation of bulldozer line construction rates. 1969. (Manuscript in preparation, Pacific Southwest Forest & Range Exp. Sta., Riverside, Calif.)

(Banks and Frayer 1966), State forestry departments (California Division of Forestry 1964), and forestry schools (Steele 1961). For certain types of forces, productivity data from different sources appear not to be in good agreement.

Handcrew

Rate of handline production may be given for line construction (building), line holding, and for held line (construction and holding combined). Five of the Forest Service notebooks list held line and five list line construction (Table 1). Three of the latter also give line holding requirements so that held line can be computed. Only the California Region, R-5, lists data in all three categories.

Line construction data for most areas are based on actual tests; line holding requirements on experience judgements. The two are combined to arrive at production of held line.

The basic size of production unit for all Regions, except R-9, is one man and productivity is expressed as chains of line per man per hour. Region 9 bases productivity on a 3-man crew. The productivity of larger sized crews with allowances for inefficiencies of size above a certain number and for fatigue can be calculated in most instances. Only Regions 1 and 9 give basic handline production rates by size of crew; Regions 1 and 2 by type of crew, Table 2.

Handcrew productivity is affected by several factors in addition to fuel resistance to control. Among these are severity of burning conditions, size of crew, type of worker, and fatigue. Night work slows productivity about one-half in Region 9, according to their Fire Overhead Notebook (1957). Productivity data in the present report are for average conditions except as noted. The literature cited provides more detailed data for determining manpower requirements for other than average conditions for most Regions.

Table 2.--Rate of construction of handline by type of worker and fuel resistance to control for Regions 1 and 2.^{1/}

Type of Worker	Construction Rate ^{2/}			
	Low	Medium	High	Extreme
	<u>Chains per man hour</u>			
Smokechasers, Guards ^{3/}	3.3	2.0	.8	.25
Trained Forest Crews	2.5	1.5	.6	.2
Untrained Woods Workers	1.25	.8	.3	.1
Pick-up Fire- fighters	.8	.25	.08	.02

^{1/} From Fireline Notebooks, R-1 (1966) and R-2 (1961).

^{2/} Apparently both Regions use the same data.

^{3/} Includes smokejumpers.

Handline production rates are usually based on the work of smokechasers or guards--the best-trained, best conditioned, and highest producing type of line worker. Other recognized types of workers are trained forest crews, untrained woods workers, and pick-up firefighters, in decreasing order of productivity. Productivity by type of worker and Region is summarized in Table 2. Smokechasers and guards can produce 12 times as much work as pick-up firefighters in extreme resistance to control fuels, according to the table. Apparently, both Region 1 and Region 2 use the same productivity figures. Factors for reducing productivity estimates in the dispatching guides when less productive workers are used can be computed from the data in Table 2 for the applicable Regions. The Southwest Firefighters (Indians) not specifically mentioned in the Notebooks would compare favorably with smokechasers and guards, the most productive class of worker.

The most common crew sizes are 3, 4, 6, 17, 23, and 42 men. Smaller crews generally are more efficient, other things being equal.

Table 3 presents a comparison of held handline production rates from seven sources and five Forest Service Regions. Rates vary by as much as a factor of 20. Although all data are not strictly comparable because of differences in fuel type, size of crew, and, possibly, burning conditions, there appears to be large unexplained variation.

Table 4 presents a comparison of line construction rates from nine sources and five Forest Service Regions. Rates vary by as much as a factor of 25. This much variation appears unreasonably large even allowing for differences in the factors mentioned earlier. A recent

Table 3.--Rate of production of held handline by source of
data and fuel resistance to control classes.

Source	Production Rate			
	Low	Medium	High	Extreme
	<u>Chains per man hour</u>			
R-3, Firefighting Overhead Notebook (1965) ^{1/}	7	4	1.4	None
R-4, Firefighting Overhead Notebook (1962)	6	3	1.2	None ^{2/}
R-4, Hanson & Abell (1941)	1.14	.20	.14	.08
R-5, Fireline Note- book (1963) ^{3/}	<u>4/</u>	<u>4/</u>	<u>4/</u>	<u>4/</u>
R-7, FSM Supplement (1964) ^{2/}	2.5+	2.1	1.4	1.0-
R-8, FSM Supplement	3.01+	1.51-3.00	.76-1.50	0-.75
R-9, Fire Overhead Notebook (1957) ^{6/}	5.3	2.7	1.3	.68

^{1/} For average worst burning conditions.

^{2/} Condition not considered existing in R-4.

^{3/} 17 fuel types arbitrarily grouped into four resistance to control classes.

^{4/} In the form of alinement charts, Appendix. Difficult to arrive at an average figure.

^{5/} Identical data in Banks' and Frayer's Fire Control Notes article (1966).

^{6/} Converted from data for 3-man crew in northern forest. On southern forests crews produce twice this much.

Table 4.--Rate of construction of handline by source of data
and fuel resistance to control classes.

Source	Construction Rate			
	Low	Medium	High	Extreme
	<u>Gains per man hour</u>			
R-1, Fireline Notebook (1966) ^{1/}	1.96	1.14	.45	.14
R-1, Stilling (1966) ^{2/}	.30	.15	.05	.02
R-2, Fireline Notebook (1961) ^{1/}	1.96	1.14	.45	.14
R-5, Fireline Notebook (1963) ^{3/}	4.97	3.18	1.26	.52
R-5, Pirsko et al (1966) ^{3/}	--	.83	.51	.55
R-5, Stevenson (1961) ^{3/ 4/}	--	.46	.23	.23
R-6, Fireline Notebook (1965) ^{5/}	4.35	3.15	1.22	.46
R-6, Matthew (1940) ^{6/}	--	.55	--	--
R-10, Fireline Notebook (1966)	4.00	1.30	.70	.40

^{1/} Average of four classes of workers.

^{2/} Computed from data for 100-man crews of pick-up fire-fighters for ten daylight hours.

^{3/} 17 fuel types arbitrarily grouped into four resistance to control classes.

^{4/} Hotshot crews averaging 27 men each.

^{5/} 13 fuel types arbitrarily grouped into four resistance to control classes.

^{6/} For 10-man crews.

study by Pirsko^{4/} and verified by Lindquist^{5/} suggests that in Region 5

4/ Pirsko, A. R. How good are fire line construction rates. 1966.
(Manuscript on file, Pacific Southwest Forest & Range Exp. Sta., Riverside, California.)

5/ Ibid.

California Region existing rates for handline construction are considerably too high (U. S. Forest Service 1963). One possible reason is that the old study used selected crews under no-fire conditions, whereas the current study was done by timing regular crews on actual wildfires. Rates for Region 6 were adapted from Region 5, which explains their similarity, Table 4. Although Lindquist's study is not far enough along to include in Table 4, his technique of expressing handcrew productivity in probabilistic terms should be mentioned.^{6/} At present crew production

6/ Ibid.

rates in fireline notebooks and elsewhere are expressed deterministically i.e. a certain type of crew will build so many chains of fireline in a certain time under the conditions stated. Lindquist, on the other hand, points out that such a crew will on the average produce this much line but may produce more than or less than the average; production forms a frequency distribution around the average value. A wise fire boss recognizes this intuitively. In a critical situation where the fire must

reliably be controlled he will send more men than the table indicates; in a less critical situation he may send less. Lindquist provides guides in terms of odds or probabilities to aid the fire manager's decisions.

Bratten^{7/} has written a conversational program for a time shared

^{7/} Personal communication with Frederick W. Bratten, Pacific Southwest Forest & Range Exp. Sta., Forest Fire Laboratory, Riverside, Calif., September 1969.

computer that will calculate and display very rapidly Lindquist's handcrew production probabilities. This method is much faster than alinement charts and tables and can accomodate more variables.

Line holding requirements data from various sources are given in the Literature Cited.

Power Handcrew

Power hand tools can increase line production and decrease stress and fatigue of the operator. Several machines are under development, none of which is in widespread use as yet (California Division of Forestry 1964, U. S. Forest Service 1966). One reason for this is the wide variation in fuel types among and within Regions, making standardization difficult.

Sample production rates for two promising power tools are shown in Table 5. A flail trencher crew consisting of two men plus machine, four men plus machine, or six men and two machines is suggested.

Bulldozer

Table 6 presents a comparison of bulldozer line construction rates

Table 5.--Power-assisted handline construction rate by type
of machine and fuel resistance.

Type of Machine	Construction Rate		
	Light	Medium	Heavy
	<u>Chains per man hour</u>		
R-5, Circular & Bow Saws, CDF (1964) ^{1/}	.68	.54	.46
R-1, Flail Trencher U.S. Forest Service (1966a) ^{2/}	-	13.6	-
R-1, Pulaski (hand) U.S. Forest Service (1966c) ^{2/}	-	6.7	-

^{1/} Average of two best saws each type building ten-foot wide line in California brush fuels. Rate converted from 6-man crew.

^{2/} Compared in same fuel resistance to trenching, 15-minute work period, line ten inches (approximately) wide.

Table 6.--Rate of bulldozer fireline construction by source of data, machine size, and fuel resistance to control classes. One unit in single pass tactic.

Source	Construction Rate											
	D-8				D-7				D-6			
	Low	Med.	High	Ext.	Low	Med.	High	Ext.	Low	Med.	High	Ext.
					Chains per unit hour							
R-1, Fireline Notebook (1966) ^{1/}	--	--	--	--	50.0	20.0	8.0	4.0	--	--	--	--
R-1, Steele (1961)	33.5	26.0	13.2	11.5	29.2	22.2	11.0	8.0	30.0 ^{2/}	24.0 ^{2/}	11.5 ^{2/}	--
R-1, Stilling (1951) ^{3/ 4/}	--	--	7.5	4.0	--	17.5	--	--	50.0 ^{6/}	12.5	--	--
R-2, Fireline Notebook (1961) ^{1/}	--	--	--	--	50.0	20.0	8.0	4.0	--	--	--	--
R-3, FF Over. Note. (1965) ^{3/ 4/}	--	--	7.5	4.0	--	17.5	--	--	50.0 ^{6/}	12.5	--	--
R-4, FF Over. Note. (1962) ^{3/ 4/}	--	--	7.5	4.0	--	17.5	--	--	50.0	12.5	--	--
R-5, Fireline Notebook (1963), (1948) ^{5/}	--	47.0	41.0	--	--	43.4	34.2	--	--	41.0	30.4	--
R-5, C.D.F. (1964)	--	--	--	--	86.0	92.0	62.5	--	62.5 ^{6/}	55.0 ^{6/}	27.4 ^{6/}	--
R-6, Fireline Notebook (1965) ^{5/}	--	47.0	41.0	--	--	43.4	32.2	--	--	41.0	30.4	--
R-9, Fire Over. Note. (1951) ^{1/ 7/}	--	--	--	--	50.0	25.0	12.0	6.0	--	--	--	--
R-10, Fireline Notebook (1966) ^{5/}	--	47.0	41.0	--	--	43.4	34.2	--	--	41.0	30.4	--

^{1/} Average all sizes of machine.

^{2/} Easy soil only.

^{3/} For two-dozer team; reduce by 10-20 percent to equal single unit.

^{4/} Average rate per hour for 10 daylight hours.

^{5/} Medium brush and heavy brush.

^{6/} D-4 dozer; increase by 2-10 percent to equal D-6.

^{7/} Includes line holding.

from eleven sources and eight Forest Service Regions. More detailed data are given in the Literature Cited. All data are not strictly comparable as noted in the table footnotes. But, with the exception of regional differences in fuel type, data bases are believed to be sufficiently similar so that broad comparisons can be made.

As nearly as could be determined, all rates are for single pass line construction. Only the Region 9 data include line holding. Rates for Regions 1, 3, and 4 are for two-unit teams, whereas the rest are for a single unit. Two units ordinarily produce about 20 percent more line and build a stronger line than two single units. However, tabular rates for the two-unit teams are generally lower, in one instance by a factor of 14 compared to the one unit. One unit ordinarily consists of three men plus the machine.

In general, there is great variability in the bulldozer data. It seems doubtful that variations in fuel types and different assumptions among sources could account for all of this. At the present time there is no uniform nationwide basis for rating fuels among Regions for purposes of fire planning and fire control. Resistance ratings are relative within a Region and apply strictly only to that Region. There is an urgent need for a national fuel rating system for fire control.

Plow

Only Forest Service Region 9 lists the productivity of tractor-plows in its fire overhead notebook. Several other sources mention isolated instances of tractor-plow productivity (Ames 1953; Couch 1960; Williams 1950). The available data are summarized in Table 7.

Table 7.--Rate of tractor-plow fireline construction by source
of data and fuel resistance to control classes.

Source	Construction Rate			
	Low	Medium	High	Extreme
	<u>Chains per hour</u>			
R-9, Fire Overhead Notebook (1957) ^{1/}	100	50	25	12
R-8, Ames (1953)	200 ^{2/}	170 ^{3/}	--	--
R-8, Couch (1960)	--	120 ^{4/}	--	--
R-8, Williams (1950)	--	50.6 ^{5/}	--	--

1/ Held line per 3-man crew; northern forests.

2/ Maximum for light tractor.

3/ Maximum for heavier tractor.

4/ Average in all southern fuels except swamps.

5/ Held line.

The tractor-plow unit usually consists of three men plus the machine. Most commonly a unit works singly. Occasionally two or more units will work in parallel if an extra wide line is required to be built in a short period of time. In dense timber it may be necessary to send a bulldozer ahead to push over trees to allow the tractor-plow to pass. In swamps two units may work in tandem so that they can free one another should one bog down.

Air Tanker

The Forest Service fireline notebooks contain no information on the productivity of air tankers. However, they do contain data on tank capacity, cruise speed, drop speed, maneuverability, suggested types of target for different types of craft, and dispatching guidelines. Some regional notebooks also list speed, cargo and passenger capacities of non-tanker aircraft. These data are required in order to compute delivery rates to the fireline and overall air tanker productivity.

For initial attack on fires at the present time liquid drops are used primarily to buy time; to hold the fire until ground forces arrive. Direct attack may be used when fires are small. Later in the fire, drops are used to reinforce the line at critical points and to handle spot fires and slopovers. In nearly all cases, handcrews are used in conjunction with air attack. The indirect attack tactic usually is used (U. S. Forest Service 1965). Tankers are not considered a primary line building force. Thus, the usual units of line production chains of line constructed per hour may not be as applicable for air tankers as for handcrews or bulldozers, for example. However, air tanker productivity ulti-

ately must be at some rate whether it be length of effective swath or area of effective swath laid down per unit time.

To date, evaluations of air tanker productivity on actual fires have, of necessity, been very general and non-quantitative. Rating terms include "effective," "ineffective," or "not needed." Each incident usually involves only one type of tanker in one specific fire situation. There is no replication nor are two or more aircraft types compared under identical conditions of fuel, topography, weather, and fire behavior. The difficulties of determining relative effectiveness of aircraft types are obvious. Yet controlled tests involving actual drops on test fires are very expensive to conduct. Opinion surveys among air tanker experts of relative effectiveness of types of tankers in a variety of situations have recently been completed (Storey and Cooley 1967).^{8/}

^{8/} Maloney, J. E. and Greulich, F. E. A mathematical model of the aerial tanker fire retardant delivery system of the California Division of Forestry. Fire Econ. Working Paper No. 11. 1966. (Unpublished report on file, School of Forestry, Univ. of Calif., Berkeley.)

Numerous calibration drops from air tankers have been conducted since about 1955, to determine pattern of swath and concentration received on the ground in open areas, under vegetation (fuel) canopies, and interception by canopies. One source conducted a series of calibration drops followed by drops on actual fires in identical fuel types (Storey et al 1955). Sample data are presented in Table 8.

Table 8.--Length of fireline retarded and extinguished by
440-gallon TBM air tanker drops in North Carolina.

BORATE^{1/}

Fuel Type And Resistance	Relative Fire Intensity	Retarded		Extinguished	
		Length ^{2/}	Min. Appl. Rate	Length ^{2/}	Min. Appl. Rate
		<u>Feet</u>	<u>Gal./ 100 Ft.²</u>	<u>Feet</u>	<u>Gal./ 100 Ft.²</u>
Low Pocosin (L)	Very Low	300	.5	300	.5
High Pocosin(H)	Medium	250	.3	230	.4
Open Cane (M)	Medium	300	.4	250	.6
Overstoried Cane (H)	Low- Medium	300	.5	280	.6
		<u>WET WATER^{3/}</u>			
Low Pocosin(L)	Very Low	200	.8	200	.8
High Pocosin(H)	Medium ^{4/}	300	.2	250	.3
Open Cane(M)	Medium ^{4/}	300	.5	280	.6
Overstoried Cane (H)	Low- Medium ^{4/}	350	.2	300	.5

1/ Indirect attack.

2/ Width of liquid pattern approximately 15-20 percent of pattern length.

3/ Direct attack.

4/ Flank fire or head-flank fire.

However, these tests were not replicated and indicated rates may be too low. The generally accepted figure for air drop effectiveness is 2-4 gallons per 100 square feet in most western fuel types. A fair estimate of effective length of swath probably could be obtained by applying this concentration to the concentration patterns obtained in previously conducted calibration tests. These data are fairly numerous for most types of aircraft and many fuel types.

Accuracy of hitting the intended target with air attack is a problem not present with ground attack. Successive drops in tandem may not overlap sufficiently to prevent gaps in the line, or drops aimed at the fireline may fall in the burned area and not be effective. Allowances for accuracy must be made in estimating number of drops required in a given situation.

Helitanker

Most of the observations on fixed-wing air tankers also apply to helitankers. None of the Forest Service regional notebooks contain any information on helitanker productivity and only three, all in the West, list liquid carrying capacities. General guidelines for their use are presented. However, the helitanker is a relatively new tool and its utility has only recently been widely accepted. Recent breakthroughs in light, powerful engine design, permitting the lifting of larger loads, should greatly increase its utility for fire suppression. Recent tests suggest that under many conditions in the western United States, late model helicopters equipped with new accessories and adequately supplied can drop as much liquid as most fixed-wing tankers, and with greater accuracy and economy (Davis 1963).

Presumably, a concentration of 2-4 gallons per 100 square feet would be required to handle a spot fire or length of fireline in direct attack similar to fixed wing air tankers. Sample concentration patterns for one make of helitank are shown in Table 9. These suggest, very approximately, what the effective length of swath in a fire situation might be.

As with air tankers, ground crews are needed in conjunction with helitanker attack to hold and consolidate gains made by air drops. Manpower requirements are not specified in the literature.

Drop placement accuracy for helitankers ordinarily is better than for air tankers since helitankers can drop at very low speed, even hovering if need be.

Pumper

Pumper and ground tankers frequently are used in initial attack on forest fires, usually in direct attack strategy. In most cases, handcrews are required to work with the nozzleman. It is standard practice for handcrews to follow up and build a line to mineral soil completely around the fire. Pumpers are similar in effect to air tankers except that their effect is comparatively short-term because, at the present time, they pump mainly water. Presumably, concentrations of liquid required to subdue the fire would be similar to air attack, 2-4 gallons per 100 square feet. Less total quantity of liquid should be required to hold a given length of fireline compared to aerial delivery, however, since application rates can be controlled more accurately. There would be less "overkill" compared to air attack.

Table 9.--Sample concentration patterns of three liquids
dropped in 100-gallon loads from a Bell 47-G
helicopter.

Retardant	Concentration (Gallons per 100 sq. feet) ^{1/}									
	1		2		3		4		5	
	Leng.	Wid.	Leng.	Wid.	Leng.	Wid.	Leng.	Wid.	Leng.	Wid.
					<u>Feet</u>					
Water	130	20	115	17	102	14	86	13	82	12
CMC	110	15	102	14	97	13	90	12	85	10
Algin Gel	100	14	90	12	70	10	52	8	41	5

^{1/} Dropped in the open from 36 feet above ground at 28 mph. Measurements taken from concentration pattern diagrams. Maximum length and average width (no serious gaps).

Only Region 9 lists pumper productivity in its fire overhead notebook (1957). These data are shown in Table 10. Production rates are for a 3-man crew, the normal size crew in the Region. Other Regions use 3 to 5-man crews on their pumpers. Fireline notebooks for other Regions list principles of water use.

Helicopter and Helitack

Helicopters are being used more and more to ferry firefighters from point to point on fires. One reason for this has been the advent of large capacity craft. Crews of men arrive faster, fresh, and in condition to do more work. Experiments are underway on helicopter operations at night for delivering men and equipment but not for air attack.

The helitack crew is a special form of helicopter delivered firefighter. These crews are specially trained in operating from helicopters in initial attack. The technique has worked well in trials in northwest California. It is particularly useful on fires in steep and inaccessible areas.

Because they begin work fresh, both the helitack crew and aerially delivered firefighters probably could be expected to build more line than the tabular figures for average rate of handline production mentioned earlier. Some notebooks have provisions for correcting for crew fatigue while others do not.

The Region 1 fireline notebook is the only one that contains data on flying speed, passenger capacity, and load capacity of various makes of helicopters (1966b). These data are needed to calculate delivery rates of firefighters to the fireline and overall productivity rates.

Table 10.--Rate of pumper held fireline construction by
fuel resistance to control, Region 9, 3-man crew.

Production Rate ^{1/}			
low	Medium	High	Extreme
50	<u>Chains per hour per crew</u>		
	25	12	6

^{1/} Rough estimates for northern forests.

The recently-developed helijump technique is a variation of helitack. Crew productivity would be about the same for both.

Smokejumper

Smokejumping is another means for delivering handcrews to fires by air. Their use is well established in the West. Crew productivity probably would exceed the highest rate for smokechasers and guards listed in Table 1.

The fireline notebooks for Regions 1, 3, and 4 list passenger capacity, cargo capacity, and flying speed for several types of fixed-wing aircraft including smokejumper transports.

Other

There are other items that provide minor assists to handcrews in producing line such as backpack pumps and falling saws. These items will not be considered in this report.

Rate of travel by walking and vehicle transport have a bearing on overall crew productivity on a fire. However, these data are readily available from other sources although not in the regional notebooks.

RATES OF SUBSTITUTION OF FORCES

Trade-offs or the substitution of one type of suppression force for another are routinely made in initial attack and during later stages of forest fires. Some general guidelines for this are available in most of the Forest Service fireline notebooks, but there are very few quantitative data. Actual experience in fire control remains the best guide. The lack of more specific rules to guide dispatching on initial attack probably reflects two things: the dearth of good

production rate data in specific situations on the one hand and the lack of knowledge of the constraints or limitations in the use of suppression forces in these situations on the other.

Only the regional notebook for Region 9 specifically lists rates of substitution among forces (1957). Included are handcrew, pumper, tractor-plow, and bulldozer. Aids for applying these data to compute probabilities are presented in the source documents, Literature Cited. Constraints are noted in general terms. Tabular rates are rough estimates and apply only to northern forests in Region 9.

Table 11 presents the force trade-off data for Region 9 in the form of productivity ratios based on handcrew productivity. For the conditions stated, the tractor-plow, the bulldozer, and the pumper are six times, three times, and three times as productive, respectively, as the handcrew. Stated another way, the tractor-plow is the equivalent of six handcrews, or two bulldozers, or two pumpers; the bulldozer and the pumper are equally productive.

A few data from three other Regions are available for comparison. Bulldozer ratios for Region 1 agree fairly well with those for Region 9, but the one bulldozer ratio available for Region 2 does not (Stilling 1951). The tractor-plow ratio for Region 8 is eight and one-half times that for Region 9 (Couch 1960). It should be kept in mind, however, that there is no national basis for rating fuels for resistance to control. Ratings are relative and apply strictly only within a Region. A fuel rated medium resistance in one Region might rate high resistance in another whose fuels generally are less of an obstacle to line construction.

Table 11.--Productivity of the tractor-plow(T-P), the bulldozer(B), and the pumper(P) expressed as a ratio to handcrew(H) by source of data and fuel resistance.

Source	Resistance to Control											
	Low			Medium			High			Extreme		
	$\frac{T-P}{H}$	$\frac{B}{H}$	$\frac{P}{H}$	$\frac{T-P}{H}$	$\frac{B}{H}$	$\frac{P}{H}$	$\frac{T-P}{H}$	$\frac{B}{H}$	$\frac{P}{H}$	$\frac{T-P}{H}$	$\frac{B}{H}$	$\frac{P}{H}$
R-1, Stilling (1951) ^{1/}	-	2.5	-	-	1.5	-	-	2.2	-	-	3.0	-
R-2, Fireline Notebook(1961) ^{2/}	-	-	-	-	17	-	-	-	-	-	-	-
R-8, Couch (1960) ^{3/}	-	-	-	40	-	-	-	-	-	-	-	-
R-9, Fireline Notebook (1957)	6	3	3	6	3	3	6	3	3	6	3	3

^{1/} Based on D-4, D-6 and D-7, D-8 and larger, and D-8 and larger bulldozers for L,M,H, & E fuel resistance, respectively.

^{2/} Based on D-6 bulldozer.

^{3/} "All varieties" of fuels in the South

^{4/} Based on 3-man crews.

Regions other than Region 9 essentially do not state rates of substitution of forces as such. However, fairly good estimates of trade-offs between certain forces probably can be made by comparing the productivity data contained in the Regional notebooks. This is limited to handcrews and bulldozers for nearly all Regions because of shortages of data. Care should be taken to see that conditions affecting one force also affect the other. For example, it is not safe to use bulldozers on slopes exceeding 60 percent whereas handcrews can be used. Air attack would be another possibility in this situation.

None of the sources list the trade-offs of air attack and other forces although most of them give suggested guidelines for when to consider using air attack. Guidelines are becoming more specific each year. The latest Forest Service Manual Supplement for Region Five specifies the wind speed above which air tankers will not be permitted to fly and the fire load index above which air tankers ordinarily should be used in initial attack (1965c). The remaining guidelines are only expressed qualitatively.

DISPATCHING AND PROBABILITY GUIDES

Dispatching guides and guides for calculating probabilities were explained briefly in an earlier section. As the names imply, solutions using the guides are, at best, only reasonable approximations of the actual rates of spread or forces required. Presumably factors in the guide are based on the best information available at the time the guides were prepared. However, most of the basic studies behind the guides date from the 1930's and 1940's and, as we have seen, productivity

data are available in quantity only for handcrews and bulldozers. This is reflected in the incompleteness of the guides. As was indicated earlier, at least some of these data may be suspect. Very few data are referenced to basic studies so they can be checked. Those that can be checked consider only a few of the many factors of the environment and condition of crews and equipment affecting force productivity.

None of the correction factors of wind speed, slope, etc. for computing rate of spread using the guides are referenced to basic studies. In general, rate of spread data are very scarce due primarily to a basic lack of understanding of how fires burn and spread. And there is considerable disagreement among the experts as to accuracy of the few spread relationships that have been developed.

For the reasons cited above there seems to be little point in comparing regional solutions using the guides. However, a cursory examination indicates that for a particular type of guide solutions would be widely divergent among Regions, other things being equal.

None of the dispatching or probability guides attempt to compute trade-offs among forces or mixed force requirements since, under the circumstances, this would be difficult indeed.

CONCLUSIONS AND RECOMMENDATIONS

Productivity data for fireline building forces are available in reasonable quantity for only two of the nine types of forces commonly used in the United States, handcrews and bulldozers. Data for the other seven forces including tractor and plow, power assisted handcrews, air tankers, etc. are scanty or non-existent. Data on trade-offs or

rates of substitution among forces including handcrews and bulldozers are very meager. The accuracy of solutions using existing dispatching and probability guides also suffer from the lack of good data on fire behavior.

Although the quantity of handcrew data is adequate, its quality is suspect. The same is true for bulldozer data for slightly different reasons. A simple comparison of handcrew productivity among Forest Service Regions indicates large variations that apparently cannot be explained by different conditions of fuel resistance to control, crew size, and type of crew. Results of a recent research study for one Region verified their experience that existing rates in use since 1938 are much too high. The corrected rates bring them more in line with those of other Regions although variation among Regions still is large. It would appear, based on present indications, that handcrew data for other Regions should be similarly re-examined. But specific comparisons cannot be made because, with the exception of (former) Region 7 and Region 5, the basic data or research reports behind the tabular rates are no longer available.

At the present time, assuming correct basic data, probably the "fireline notebook" type of presentation provides acceptable accuracy for applying productivity data in actual fire situations. Solutions are recognized as only providing indications or reasonable estimates of actual rates. Also, using manual techniques for data analysis, the only ones currently available, limits the number of variables that can be handled as rapidly as necessary. However, the computer-based

mathematical models of fire control currently in development can handle an almost unlimited number of pertinent variables. Except for the recent studies of handcrew and bulldozer productivity in California, existing data are probably too inaccurate and too limited to support these models. It is recommended that other Regions restudy their handcrew productivity data, preferably using some of the new techniques and methods developed in the California study. The probabilistic approach to estimating crew productivity used in this study is particularly recommended.

Bulldozer productivity data are available in reasonable quantity, for all Regions using this type of force. But, as was the case with handcrews, bulldozer data may be suspect. A simple comparison among Regions shows large variations that apparently cannot be explained by fuel resistance, slope, etc. And, unlike handcrews, advances in equipment design such as the torque converter can greatly increase the performance of a given class of machine. This is entirely independent of operator and crew performance. Apparently in recognition of this the California Division of Forestry recently completed the field phase of a study of bulldozer productivity. This seems long overdue since the current bulldozer data in Region 5 Fireline Notebooks are based on a study conducted in 1948. Data from other Regions probably are similarly out of date judging from the publication dates of the few original studies that are available. As was the case with handcrew data mathematical models of fire control need, as input, better basic data on bulldozer productivity than now exist. Productivity data for

other forces likewise suggest wide variations among Regions, although data are too scanty to make meaningful comparisons possible.

Data on trade-offs or rates of substitution of forces, although rather meager, show wide variations among Regions. This suggests the need for more definitive data than are presently available to support advanced fire control systems.

Solutions of force required to suppress a fire obtained from dispatching and probability guides in the fireline notebooks are only as good as the data on fire spread and force productivity on which they are based. As we have seen, force productivity data are limited in quality and coverage. Estimates of length of fireline requiring treatment are of limited accuracy due to a general lack of good data on fire behavior. Models of fire spread and control will require much better data on fire spread and force productivity than currently exist. Fire behavior studies are currently underway that should provide better data in the near future. It is recommended that they be continued and, if possible, accelerated.

In order for mathematical models of fire behavior and control to be applicable nationwide, systems for rating fuels and weather from a fire effect standpoint must be applicable nationwide. Good progress is being made on a national fire danger rating system. A study to develop a national system for rating fuel for rate of spread and resistance to control is underway but not as far along. Such a system is urgently needed.

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